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A New Measurement of the W Mass

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Abstract

The CDF collaboration has measured the mass of the W boson using 5718 $W \to e\nu$ and 3268 $W \to \mu\nu$ events collected in $\sim$ 20 pb^{-1} in Run Ia at the Fermilab Tevatron. The measurement yields M$_W$=80.41±0.18 GeV/c^2.

1 Introduction.

The mass of the W boson, M_W, is given at Born level by $M_W = g/\sqrt{2} < v >$, where g is the SU(2) coupling constant, and $< v >$ is the vacuum expectation value of the Higgs field[1]. Radiative corrections give a dependence of the W mass on the top quark and Higgs masses[2]. A precise measurement of the W mass, combined with other electroweak precision measurements and the measurement of the top mass[3], tests consistency of the standard electroweak model, and within the framework of the model, can give an indication of the mass of the Higgs boson. The CDF collaboration has just finished the W mass analysis of the data from Run Ia, which extended from August of 1992 to the end of May of 1993. The result, using data from $\sim$ 20 pb^{-1}, has an uncertainty that is half the size of that of the previous best measurement. The analysis is described in two papers that were submitted for publication[4] in the week prior to this conference: a long detailed summary of all the details (the devil is in the details in a measurement such as this), and a Letter for general consumption. The interested reader is referred to these papers: here we will take a brief 'walk-through' of the analysis, ending with a comparison of the constraints in the M_W-$M_{\rm top}$ plane from LEP and the new CDF measurements of M_W and $M_{\rm top}$[3].

2 Overview of the Analysis

A precise measurement of a mass done by reconstructing the decay products, in contrast to one in which the primary measurement is cross-section measurements made in an energy scan of the accelerator, depends critically on the energy scale calibration of the detector[5]. As this is a lineshape measurement, understanding the energy resolution is also critical.

The momentum scale is determined by measuring the J/ψ mass using a large sample of $J/\psi \to \mu\mu$ events. This is the key scale in the mass measurement in the W$^{\pm} \to \mu^{\pm}\nu$ channel. For the W$^{\pm} \to e^{\pm}\nu$ channel, the energy scale of the central electromagnetic calorimeters is determined by measuring both the calorimeter response ('E') and the momentum of the track in the magnetic spectrometer ('p'), and then setting the calorimeter energy scale from the measured and predicted E/p distributions for electrons in the W$^{\pm} \to e^{\pm}\nu$ sample.

The response of the detector to the recoil energy is measured using Z$^0 \to e^+e^-$ decays, in which the transverse momentum (p$_{\rm T}$) of the Z is measured directly from the lepton
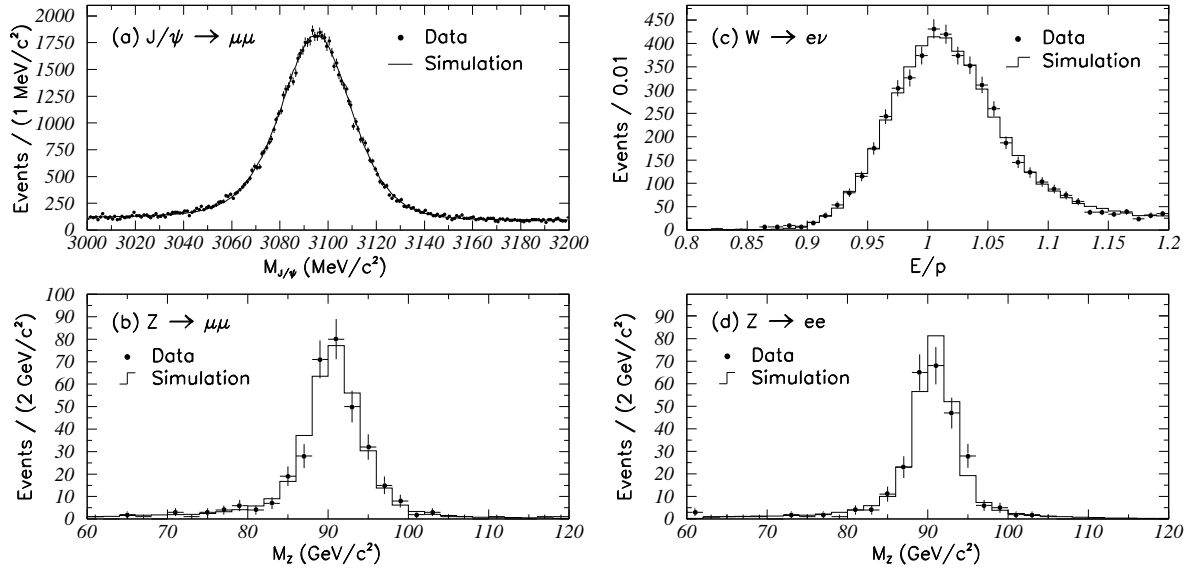
Figure 1: a) The dimuon mass spectrum near the J/ψ mass peak, used to normalize the momentum scale. b) The dimuon mass spectrum near the Z mass peak, used to determine the momentum resolution. c) The E/p spectrum for electrons from the $W^\pm \rightarrow e^\pm \nu$ sample, used to determine the energy scale. d) The dielectron mass spectrum near the Z mass peak, used to determine the energy resolution. The solid line in (a) and the histograms in (b), (c), and (d) are Monte Carlo simulations, including radiative effects.

momenta, to form a 'look-up' table of the measured response for a given boson p_T. This bypasses the difficult task of constructing a many-parameter model to fit the recoil response.

The W mass measurement is performed by comparing the lineshape of the measured transverse mass[6] with 'templates' in transverse mass, which are constructed by Monte Carlo for a range of W masses, using measured values for the energy scale, resolution, and response to the recoil. The latter are varied within the limits set by measurement to estimate the respective uncertainties. The requisite knowledge of the transverse momentum distribution of the W is more precise than is available by measurement; this spectrum is also varied within limits set by the data to estimate the uncertainty.

An enumeration of the data sets employed in this analysis provides a compact overview of how the relevant energy scales and resolutions are determined. The data sets and their uses are:

1. A sample of $\sim$60,000 $J/\psi \rightarrow \mu\mu$ events to set the spectrometer momentum scale.
2. A sample of $\sim$2000 $\Upsilon \rightarrow \mu\mu$ events to check the momentum scale.
3. A sample of 330 $Z \rightarrow \mu\mu$ events to:
   a. Measure the magnetic spectrometer momentum resolution $\delta p/p$.
   b. Check the magnetic spectrometer momentum scale.
4. A sample of 140,000 inclusive electrons $(e + X)$ to:
   a. Balance the response of the 478 towers of the central electromagnetic calorimeter.
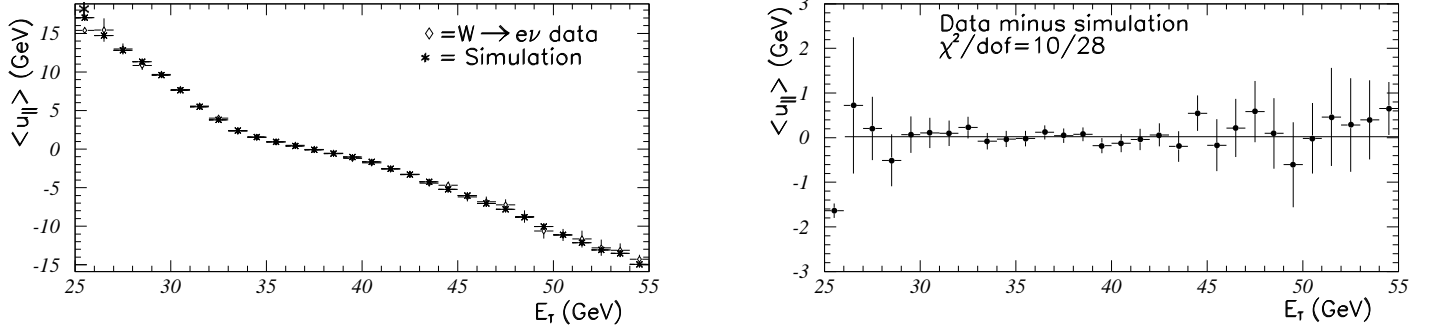   b. Align the 84 layers of sense wires in the central tracking chamber of the spectrom-

Figure 2: Left: Data versus predicted value of $< u_\parallel >$ as a function of the electron E_T for the $W \to e\nu$ data. Right: The residuals of the data minus the simulation.

eter.

5. A sample of 555 $Z \to ee$ events to:
   a. Map the response of the full calorimeter system to recoil energy.
   b. Measure the energy resolution, $\delta E/E$, of the central electromagnetic calorimeter.
   c. Check the energy scale of the central electromagnetic calorimeter.
6. A sample of 3268 $W \to \mu\nu$ events to measure the W mass.
7. A sample of 5718 $W \to e\nu$ events to:
   a. Set the energy scale from the momentum scale by using E/p.
   b. Measure the W mass.

The momentum scale is determined from the measurement of the J/ψ mass, $M_{J/\psi} = 3097.3 \pm 1.6$ MeV/c^2 (see Figure 1a). The momentum scale is corrected by a factor of 0.99984 ± 0.00058 for the J/ψ mass to agree with the world average of 3096.88 ± 0.04 MeV/c^2 [7], where the uncertainty on the correction factor includes accounting for the extrapolation to the W mass. This corresponds to a correction of -11 ± 50 MeV/c^2 at the W mass.

The momentum resolution, $\delta p/p$, is determined from the width of the mass peak in $Z^0 \to \mu^+\mu^-$ decays (Figure 1b). We find $\delta p_T/p_T^2 = 0.000810 \pm 0.000085(stat) \pm 0.000010(sys)$, where p_T is in GeV/c.

The energy scale of the central electromagnetic calorimeter is set by comparing the lineshape in E/p (see Figure 1c) with a Monte Carlo calculation that takes into account electromagnetic radiation by the electrons.

The transverse energy of the neutrino is calculated using the charged lepton energy and the net transverse energy of all other particles (the "recoil"), $\mathbf{E}_T^\nu = -(\mathbf{E}_T^\ell + \mathbf{u})$. The recoil $\mathbf{u}$ is calculated as a sum in E_T over electromagnetic and hadronic calorimeter towers in the region $|\eta| < 3.6$. Towers in proximity to the lepton are excluded from this sum, with 30 MeV per excluded tower added back in to account for average energy flow unrelated to the lepton.

The detector response to the recoil $\mathbf{u}$ is directly calibrated using $Z^0 \to e^+e^-$ decays, for which there is a good measurement of the true p_T^Z from the measured electron energies. The $Z^0 \to e^+e^-$ event sample is used as a table from which one can look up the measured response $\mathbf{u}$ for a given $\mathbf{p}_T^Z$. We assume that the response to the recoil from a W of a given p_T is the same as that to the recoil from a Z of the same p_T. (Note that the technique does not depend on the W and Z spectra being the same).
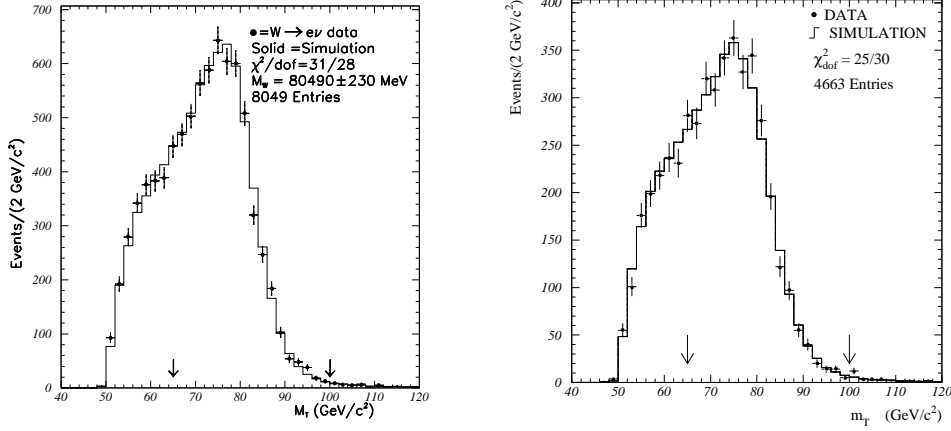
3

Figure 3: The measured spectra (points) in transverse mass for $W^{\pm} \to e^{\pm}\nu$ (left) and $W^{\pm} \to \mu^{\pm}\nu$ (right), compared to the best fit simulation template.

The remaining ingredient necessary to model the lineshape accurately in the simulation is knowledge of the p_T^W spectrum. The similarity of the p_T spectra of W and Z bosons observed in direct measurements [8] and in theoretical predictions [9] leads us to use the observed $Z \to ee$ p_T spectrum, corrected for electron energy resolutions, as an initial guess for the p_T^W spectrum. We modify the shape of this spectrum in order to match the observed $u_{\perp}$ distribution for the W events, where $u_{\perp}$ is the component of the recoil perpendicular to the direction of the charged lepton. We find that the simplest modification, scaling p_T in the p_T^Z distribution by a constant factor, gives good agreement for both electron and muon $u_{\perp}$ distributions. We consider other modifications to the shape in estimating systematic errors; the uncertainty on M_W due to the modelling of the p_T^W spectrum is 45 MeV/c^2.

This model of W production and decay works extremely well. Figure 2 shows the distribution in the mean of the recoil component along the lepton direction ($u_{\parallel}$) versus E_T. Note that effectively only a single parameter in the Monte Carlo has been 'tuned', the scale factor on the p_T^W distribution.

To extract the W mass, the transverse spectrum of the data is fit to lineshapes in transverse mass corresponding to different W masses, simulated with a leading-order (i.e. $p_T^W =0$) W Monte Carlo using the MRS D$'_-$ parton distribution functions [10]. The lineshapes include contributions from backgrounds. At each mass point, an unbinned log-likelihood is calculated for the hypothesis that the data are consistent with that mass. The log-likelihood values fit well to a parabola. The transverse mass spectra and the Monte Carlo lineshapes corresponding to the best fit mass are shown in Figure 3. We add 168 ± 20 MeV/c^2 and 65 ± 20 MeV/c^2 to the fitted masses in the muon and electron channels, respectively, to account for the effects of radiative W decay [11]. The final numbers for the two channels are $M_W^{\mu} = 80.310 \pm 0.205$ (stat.) ± 0.130 (syst.) GeV/c^2 and $M_W^{e} = 80.490 \pm 0.145$ (stat.) ± 0.175 (syst.) GeV/c^2. Combining the electron and muon results, accounting for correlated uncertainties, yields a mass $M_W = 80.41 \pm 0.18$ GeV/c^2.

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Uncertainty	ΔM_W^e (MeV/c²)	ΔM_W^μ (MeV/c²)	Common (MeV/c²)
I. Statistical	145	205	—
II. Energy Scale	120	45	45
1. Scale from J/ψ	45	45	45
2. CTC Alignment	15	15	15
3. Calorimeter	110	—	—
a. Stat. on E/p	65		
b. Syst. on E/p	90		
III. Other Systematics	130	120	90
1. e or μ resolution	80	60	—
2. Input p_T^W	45	45	25
3. Recoil modeling	60	60	60
4. Proton structure	50	50	50
5. e or μ ID and removal	25	10	5
6. Trigger bias	0	25	—
7. Radiative corrections	20	20	20
8. W width	20	20	20
9. Higher-order corrections	20	20	20
10. Backgrounds	10	25	—
11. Fitting	10	10	—
TOTAL UNCERTAINTY	230	240	100

Table 1: Summary of uncertainties in the W mass measurement.

3   A Brief Summary of the Measurement Uncertainties

The experimental uncertainties in the two channels are summarized in Table 1. The final uncertainties are 230 MeV/c² in the electron channel and 240 MeV/c² in the muon channel. Uncertainties that are in common, and hence are correlated, are estimated as 100 MeV/c². The interested reader is referred to Reference [4] for more details.

A large number of internal checks have been made in the analysis. Of the 28 checks, there are two that are more than 2 σ away from their expected value (this by itself is not surprising– the distribution of the 28 'discrepancies' fits well to a Gaussian centered on zero with an RMS of 0.98 $\pm$ 0.13). One of the two is the Υ 3S mass, which differs from the world average by 2.26 σ. Given that the 1S and 2S are much better determined, this is not a cause for concern. The second is that the mass measured for W$^+$ and W$^-$ differ by 2.6 σ. We have investigated this at length, and have concluded that it is most likely a statistical fluctuation, and that the quoted uncertainties are good estimates of the systematics on the charge-averaged mass.
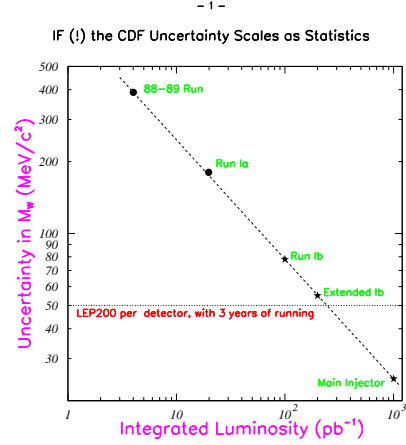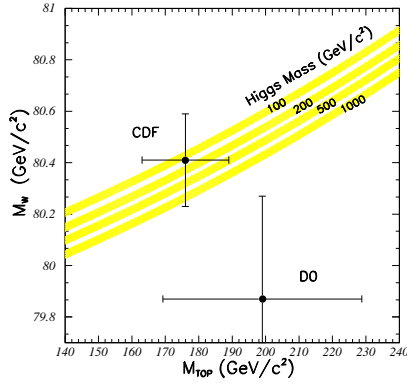
IF (!) the CDF Uncertainty Scales as Statistics

Higgs Mass (GeV/c²)
100 200 500 1000

M_W (GeV/c²)

CDF

D0

M_{TOP} (GeV/c²)

Uncertainty in M_W (MeV/c²)

88–89 Run

Run Ia

Run Ib

Extended Ib

LEP200 per detector, with 3 years of running

Main Injector

Integrated Luminosity (pb⁻¹)

Figure 4: (Left) The new measurements of M_W [4] and M_{top}[3] from CDF, and of M_{top} from D0[13]. The bands are described in Reference[12]. Figure 5: (Right) The simplest projection of the uncertainty in M_W: assuming that the systematic uncertainty scales with the statistical uncertainty.

4 Testing the Standard Model

The new measurements of the W and top masses are shown in the M_W-M_{top} plane in Figure 4 along with theoretical predictions based on LEP measurements [12]. Also shown are the D0 measurements of the W and top masses[13].

5 The Future

There is always much interest as to how well we think we can do in the future. Two points can be made: the first is that the analysis described here, with an overall uncertainty of 180 MeV/c², is from an integrated luminosity of $\sim 20\ pb^{-1}$, accumulated in Run Ia. We have at present a total more than 4 times this (adding runs Ia and Ib). At present the systematic uncertainty is scaling with the number of events just as is the statistical uncertainty (this is because the dominant systematics are measured from the data, and these measurements are themselves limited by statistics). The decrease in the overall uncertainty in M_W from the 390 MeV/c² measured in 4 pb^{-1} in the 1988-89 run to the 180 MeV/c² measured in 20 pb^{-1} follows this scaling, as shown in Table 2.

The second point is perhaps more germane. The competitiveness of the two Fermilab experiments with LEP in measuring the W mass depends on the Tevatron running schedule. Figure 5 shows how the uncertainty would decrease with integrated luminosity for a purely statistical scaling. With 200 pb^{-1} of data each of the two experiments has the possibility of being at the 60 MeV/c² level. We note that CDF has achieved accumulating 4 pb^{-1} in one week, and that the accelerator performance is still improving. Whether or not the Tevatron will be competitive with results from Run II with LEP depends critically on when Run II will occur; certainly Fermilab should accumulate as much luminosity as possible now to push the measurement down into the interesting region before LEP200 begins. It is likely that Run II will be too late to be competitive.

I would like to thank Tran Than Van and the organizers and staff of the Rencontre for an excellent conference and their warm hospitality, and my CDF colleagues for the opportunity to present these results.

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Table 2: Comparison of existing measurements of the W mass

Who	ℓ	L pb^{-1}	Evts	σ_{stat} MeV	σ_{sys} MeV	σ_{tot} MeV	$\sigma_{stat} \times \sqrt{L}$ MeV$pb^{-1/2}$	$\sigma_{stat} \times \sqrt{Ev}$ GeV	Ev/pb^{-1}	$\sigma_{tot} \times \sqrt{L}$ MeV$pb^{-1/2}$
CDF	e	4.4	1130	350	240	465	735	11.8	260	975
CDF	μ	3.9	592	530	315	620	1045	12.9	150	1225
UA2	e	13.0	2065	330	170	370	1190	15.0	160	1335
Run 1A Results										
D0	e	11	4817	160	305	345	530	11.1	440	1145
CDF	e	18.2	5718	145	180	230	620	11.0	315	980
CDF	μ	19.7	3268	205	130	240	910	11.7	165	1065
CDF	e/μ	19.7	8986	120	–	180	530	—	480	800

References

[1] See, for example, Gauge Theories in Particle Physics, I.J.R. Aitchison and A.J.G. Hey, Adam Hilger Publ. 1989.

[2] For recent reviews, see W. Hollik and W. Marciano, in "Precision Tests of the Standard Electroweak Model", ed. by P. Langacker (World Scientific, Singapore, 1994), and B. A. Kniehl, KEK preprint KEK-TH-412, Sept. 1994, submitted to Int. J. Mod. Phys. A.; J. L. Rosner, Rev. Mod. Phys., **64**, 1151 (1992)

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[5] The convention $c = 1$ allows energy, momentum, and mass to have same units, and so can be described generally as energy.

[6] The transverse mass is defined as $M_T = ((E_T^\ell + E_T^\nu)^2 - (\mathbf{E}_T^\ell + \mathbf{E}_T^\nu)^2)^{1/2}$, where $\mathbf{E}_T^\ell$ is the transverse energy of the charged lepton (electron or muon), and $\mathbf{E}_T^\nu$ is the transverse energy of the neutrino.

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